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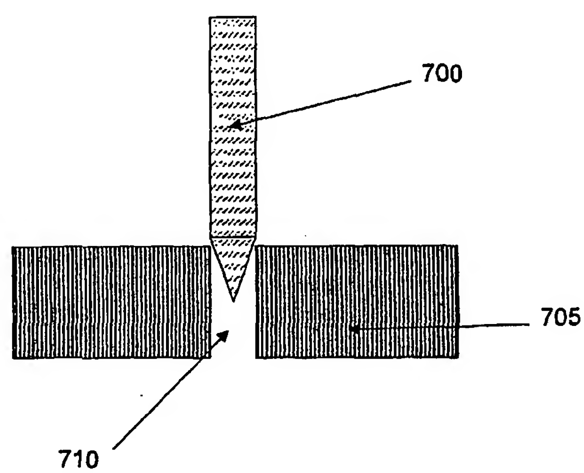
(54) Title: SEGMENTED ELECTRODE CAPILLARY DISCHARGE, NON-THERMAL PLASMA APPARATUS AND PROCESS FOR PROMOTING CHEMICAL REACTIONS



(57) **Abstract:** A plasma reactor (100) including a first dielectric (115) having at least one capillary (146) defined therethrough, and a segmented electrode (140) including a plurality of electrode segments (140), each electrode segment (140) is disposed proximate an associated capillary (146). The reactor (100) may include a second electrode (120) and dielectric with the first and second dielectrics (115) separated by a predetermined distance to form a channel (125) therebetween into which the plasma exiting from the capillaries (146) in the first dielectric (115) is discharged. The fluid to be treated is passed through the channel (125) and exposed to the plasma discharge. The fluid to be treated may be exposed to the plasma discharge both in the capillaries (146) as well as in the channel (125) between the two dielectrics (115). The plasma reactor (100) has a wide range of application, such as the destruction of pollutants in a fluid, the generation of ozone, the pretreatment of air for modifying or improving combustion, and the destruction of various organic compounds, and surface cleaning of objects.

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SEGMENTED ELECTRODE CAPILLARY DISCHARGE, NON-THERMAL PLASMA APPARATUS AND PROCESS FOR PROMOTING CHEMICAL REACTIONS

Cross-Reference to Related Applications

This application claims the benefit of U.S. Provisional Application No. 60/171,198, filed December 15, 1999 and U.S. Provisional Application No. 60/171,324, filed December 21, 1999, are all hereby incorporated by reference in their entirety.

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention is directed to system and method for generating plasma discharge and, in particular, to a segmented electrode capillary discharge, non-thermal plasma process and apparatus.

Description of Related Art

A "plasma" is a partially ionized gas composed of ions, electrons, and neutral species. This state of matter is produced by relatively high temperatures or relatively strong electric fields either constant (DC) or time varying (e.g., RF or microwave) electromagnetic fields. Discharged plasma is produced when free electrons are energized by electric fields in a background of neutral atoms/molecules. These electrons cause electron atom/molecule collisions which transfer energy to the atoms/molecules and form a variety of species which may include photons, metastables, atomic excited states, free radicals, molecular fragments, monomers, electrons, and ions. The neutral gas becomes partially or fully ionized and is able to conduct currents. The plasma species are chemically active and/or can physically modify the surface of materials and may therefore serve to form new chemical

compounds and/or modify existing compounds. Discharge plasmas can also produce useful amounts of optical radiation to be used for lighting. Many other uses for plasma discharge are available.

U.S. Patent Nos. 5,872,426; 6,005,349; and 6,147,452, each of which are herein incorporated by reference, describe a glow plasma discharge device for stabilizing glow plasma discharges by suppressing the transition from glow-to-arc. A dielectric plate having an upper surface and a lower surface and a plurality of holes extending therethrough is positioned over a cathode plate and held in place by a collar. Each hole in the dielectric acts as a separate active current limiting micro-channel that prevents the overall current density from increasing above the threshold for the glow-to-arc transition. This conventional use of a cathode plate is not efficient in that it requires the input of a relatively high amount of energy. In addition, the reactor requires a carrier gas such as Helium or Argon to remain stable at atmospheric pressure.

It is therefore desirable to develop a device that solves the aforementioned problem.

Summary of the Invention

The present invention consists of a system for generating non-thermal plasma reactor system to facilitate chemical reactions. Chemical reactions are promoted by making use of the non-thermal plasma generated in a segmented electrode capillary discharge non-thermal plasma reactor, which can operate under various pressure and temperature regimes including ambient pressure and temperature. The device uses a relatively large volume, high density, non-thermal plasma to promote chemical reaction upon whatever fluid is passed through the plasma (either passed through the capillary or passed transverse through the resulting plasma jet from the capillary. Examples of the chemistry, which could be performed using this method, include the destruction of pollutants in a fluid stream, the generation of ozone, the pretreatment of air for modifying or improving combustion, the destruction of various organic compounds, or as a source of light. Additionally, chemistry can be performed on the surface of dielectric or conductive materials by the dissociation and oxidation of their molecules. In the case of pure hydrocarbons complete molecular

conversion will result in the formation of carbon dioxide and water, which can be released directly to the atmosphere.

The reactor in accordance with the present invention is designed so that the gaseous stream containing chemical agents such as pollutants are exposed to the relatively high density plasma region where various processes such as oxidation, reduction, ion induced decomposition, or electron induced decomposition efficiently allow for chemical reactions to take place. The ability to vary the plasma characteristics allows for tailored chemical reactions to take place by using conditions that effectively initiates or promotes the desired chemical reaction and not heat up the bulk gases.

In a preferred embodiment of the present invention the plasma reactor includes a first dielectric having at least one capillary defined therethrough, and a segmented electrode including a plurality of electrode segments, each electrode segment is disposed proximate an associated capillary. Each electrode segment may be formed in different shapes, for example, a pin, stud, washer, ring, or disk. The electrode segment may be hollow, solid, or made from a porous material. The reactor may include a second electrode and dielectric with the first and second dielectrics separated by a predetermined distance to form a channel therebetween into which the plasma exiting from the capillaries in the first dielectric is discharged. The fluid to be treated is passed through the channel and exposed to the plasma discharge. If the electrode segment is hollow or made of a porous material, then the fluid to be treated may be fed into the capillaries in the first dielectric and exposed therein to the maximum plasma density. The fluid to be treated may be exposed to the plasma discharge both in the capillaries as well as in the channel between the two dielectrics. The plasma reactor is more energy efficient than conventional devices and does not require a carrier gas to remain stable at atmospheric pressure. The plasma reactor has a wide range of application, such as the destruction of pollutants in a fluid, the generation of ozone, the pretreatment of air for modifying or improving combustion, and the destruction of various organic compounds, and surface cleaning of objects.

The present invention is directed to a plasma reactor including a first dielectric having at least one capillary defined therethrough, and a segmented electrode

including a plurality of electrode segments, each electrode segment disposed proximate an associated capillary.

In addition, the present invention also provides a method of treating a fluid in a plasma reactor as described above. Initially, a fluid to be treated is passed through one or more electrode segments and associated capillaries. The fluid is able to pass through the electrode segment if the segment is hollow or made of a porous material. The fluid to be treated while being passed through the capillary is exposed to the plasma discharge prior to exiting from the capillary. In addition, or instead of, passing the fluid to be treated through the electrode segment, the fluid to be treated may be passed through a channel defined between the first dielectric and a second dielectric. In the channel, the fluid to be treated is exposed to plasma discharged from the capillary. Accordingly, the fluid to be treated may be passed and exposed to the maximum plasma density in the capillaries defined in the first dielectric as well as in the plasma region (channel) between the two dielectrics.

Brief Description of the Drawing

The foregoing and other features of the present invention will be more readily apparent from the following detailed description and drawings of illustrative embodiments of the invention wherein like reference numbers refer to similar elements throughout the several views and in which:

Figure 1a is a cross-sectional longitudinal view of an exemplary single annular segmented electrode capillary discharge plasma reactor system in accordance with the present invention;

Figure 1b is a cross-sectional lateral view of the plasma reactor system of Figure 1a along line B-B;

Figure 1c is an enlarged top view of a single electrode segment and associated capillary in the plasma reactor system in Figure 1a;

Figure 1d is an enlarged cross-sectional view of the arrangement of a single electrode segment and associated capillary in the reactor system in Figure 1a;

Figure 1e is a cross-sectional longitudinal view of another embodiment of a single annular segmented electrode capillary discharge plasma reactor system in accordance with the present invention with a hollow inner segmented electrode having a substantially uniform thickness and varied capillary hole density in the first dielectric;

Figure 1f is a cross-sectional longitudinal view of yet another embodiment of a single annular segmented electrode capillary discharge plasma reactor system in accordance with the present invention with a hollow inner segmented electrode having a non-uniform thickness and substantially uniform capillary hole density in the first dielectric;

Figure 2a is a cross-sectional longitudinal view of an exemplary embodiment of a system having two annular segmented electrode capillary discharge plasma reactors in accordance with the present invention;

Figure 2b is a cross-sectional lateral view of an exemplary embodiment of a system having eight annular segmented electrode capillary discharge plasma reactors in accordance with the present invention;

Figure 3a is a cross-sectional longitudinal view of a single rectangular shaped segmented electrode capillary discharge plasma reactor system in accordance with the present invention;

Figure 3b is a top view of the reactor of Figure 3a;

Figure 4 is a cross-sectional longitudinal view of an exemplary system having multiple rectangular shaped segmented electrode capillary discharge plasma reactors in accordance with the present invention;

Figure 5a is a cross-sectional view of an exemplary hollow pin electrode segment partially inserted into an associated capillary defined in the first dielectric;

Figure 5b is a top view of the electrode segment of Figure 5a;

Figure 6a is a cross-sectional view of an exemplary solid pin electrode segment having a blunt tip partially inserted into an associated capillary defined in the first dielectric;

Figure 6b is a top view of the electrode segment of Figure 6a;

Figure 7a is a cross-sectional view of an exemplary solid pin electrode segment having a pointed tip partially inserted into an associated capillary defined in the first dielectric;

Figure 7b is a top view of the electrode segment of Figure 7a;

Figure 8a is a cross-sectional view of an exemplary solid substantially flat electrode segment substantially flush with an associated capillary defined in the first dielectric;

Figure 8b is a top view of the electrode segment of Figure 8a;

Figure 8c is a cross-sectional view of an exemplary solid substantially flat electrode segment a portion of which extends into an associated capillary defined in the first dielectric;

Figure 8d is a top view of the electrode segment of Figure 8c;

Figure 8e is a cross-sectional view of an exemplary hollow substantially flat electrode segment substantially flush with an associated capillary defined in the first dielectric;

Figure 8f is a top view of the electrode segment of Figure 8e;

Figure 9a is a cross-sectional view of an electrode segment associated with one capillary of the first dielectric also having auxiliary channels defined therein;

Figure 9b is a top view of the embodiment of Figure 9a;

Figure 10a is a cross-sectional view of an alternative embodiment of an electrode segment associated with one capillary of a first dielectric having auxiliary channels in fluid communication with the capillary;

Figure 10b is a top view of the embodiment of Figure 10a;

Figure 11 is an exemplary surface cleaning system in accordance with the present invention;

Figure 12a is a schematic diagram of an exemplary air handler with a segmented electrode capillary discharge plasma reactor in accordance with the present invention; and

Figure 12b is an enlarged view of the segmented electrode capillary discharge plasma reactor in Figure 12a.

Detailed Description of the Invention

The segmented electrode capillary discharge, non-thermal plasma reactor in accordance with the present invention is designed so that a solid or a fluid (e.g., a liquid, vapor, gas, or any combination thereof) containing chemical agents, for example, an atomic element or a compound, is exposed to a relatively high density plasma in which various processes, such as oxidation, reduction, ion induced composition, and/or electron induced composition, efficiently allow for chemical reactions to take place. By way of example, the chemical agents may be Volatile Organic Compounds, Combustion Air or Combustion Exhaust Gases. The ability to vary the energy density allows for tailored chemical reactions to take place by using enough energy to effectively initiate or promote desired chemical reactions without heating up the bulk gas.

By way of example the present invention will be described with respect to the application of using the plasma reactor to purify or treat a contaminated fluid. It is, however, within the intended scope of the invention to use the device and method for other applications.

Longitudinal and lateral cross-sectional views of an exemplary single annular segmented electrode capillary discharge plasma reactor system in accordance with the present invention are shown in Figures 1a and 1b, respectively. The single annular segmented electrode capillary discharge plasma reactor 100 in Figure 1a includes an inlet 150 for receiving the fluid to be treated. A flow transition conduit 110 is disposed between the inlet 150 and a reaction chamber 155 to streamline the flow of fluid to be treated. That is, the flow transition conduit 110 distributes the fluid to be treated substantially uniformly prior to its introduction into the reaction chamber 155. Reaction chamber 155 includes a first dielectric 115 and a second electrode 120. The second electrode 120 is disposed circumferentially about at least a portion of the outer surface of a second dielectric 115 and extends in a longitudinal direction along at least a portion of the length of the reaction chamber 155. In a preferred embodiment, the second electrode 120 is insulated and composed of a metallic or non-metallic conductor. Throughout the description of the invention any conventional material may be used as a dielectric such glass or ceramic.

Disposed inside the reaction chamber 155 is a hollow tube 147 perforated with holes. A first dielectric 135 having capillaries 146 defined therein is disposed about the hollow tube 147. The first and second dielectrics may be the same or different materials. Interposed between the hollow tube 147 and first dielectric 135 is a segmented electrode 140 comprising a plurality of electrode segments. A power supply 130 is connected to the second electrode 120 and the segmented electrode 140.

Although shown in Figure 1a as a plate, the second electrode 120 may alternatively be a segmented electrode comprising a plurality of electrode segments. Alternatively, the second electrode 120 and second dielectric 115 may be eliminated altogether.

In the embodiment shown in Figure 1a, each electrode segment 140 is in the shape of a ring or washer having a hole 146 defined therethrough. Enlarged top and cross-sectional views of a single electrode segment 140 in the shape of a hollow ring are shown in Figures 1c and 1d, respectively. The hollow ring shaped electrode segment 140 is disposed in contact with the first dielectric 135. In an alternative embodiment, electrode segment 140 may be disposed above and separated from the first dielectric 135 by a predetermined distance, or extend any desired depth into the capillary 148. The electrode segment 140 is arranged so that the holes in the hollow tube 147, the holes 146 in the electrode segments 140, and the capillaries 148 defined in the first dielectric 135 are substantially aligned with one another. Holes in the hollow tube 147 and electrode segment 140 provide a conduit through which the fluid to be treated may be passed and exposed to the maximum plasma density in the capillaries 148 defined in the first dielectric 135 as well as in the plasma region between the two dielectrics 115, 135. It is within the scope of the invention to eliminate the hollow tube 147altogether and merely expose or treat the contaminated fluid in the plasma region between the two dielectrics.

Plasma is generated in a channel 125 between the dielectrics 115, 135 and in the capillaries 148 defined in the first dielectric 135. The capillaries 148 defined in the second dielectric 135 can vary in diameter, preferably from a few microns to a few millimeters, and can also vary in density or spacing relative to one another.

The density or spacing of the capillaries 148 may be varied, as desired, so as to generate a plasma discharge over a portion or the entire length of the reaction chamber 155. In addition, the diameter of the capillaries 148 may be selected so as to obtain a desired capillary plasma action.

In operation, fluid to be treated is received at the inlet 150 and passed through the transition conduit 110 into the channel 125 of the reaction chamber 155. If the electrode segments 140 are hollow, as shown in Figure 1d, then the fluid to be treated may also be passed through the electrode segments 140 and into the capillaries 148. A capillary plasma discharge is created in the capillaries 148 and the channel 125 upon the application of a voltage from the power supply 130. The plasma discharge produces chemical reactions that destroy the contaminants in the fluid to be treated. Accordingly, treatment of the contaminated fluid by exposure to the plasma may occur in the capillaries 148 and/or the channel 125. The plasma generated in the capillaries and channel promotes chemical reactions that facilitate processes such as the destruction of contaminants.

Figures 1e and 1f show exemplary alternative embodiments of a single annular segmented electrode capillary discharge plasma reactor in accordance with the present invention. Unlike the embodiment shown in Figure 1a in which the reactor chamber 155 includes a hollow tube, in Figures 1e and 1f, the hollow tube 147 may be eliminated as a result of using a U-shaped inner electrode 165. In both embodiments, the fluid to be treated is exposed to the maximum plasma density in the capillaries 195 defined in the first dielectric 170 as well as in the plasma region between the two dielectrics 170, 175. The reaction chamber in Figures 1e and 1f has an inlet 160 directly connected to a plurality of electrode segments that together form a hollow inner segmented electrode 165 in contact with a first dielectric 170. Capillaries 195 are defined in the first dielectric 170 along its length in a longitudinal direction. Opposite its open end the first dielectric 170 has a closed end 185, proximate an outlet 190, to prevent the fluid to be treated from escaping from the reaction chamber without being subject to chemical reactions when exposed to the plasma.

Despite their overall similar configuration, the embodiments shown in Figures

1e and 1f differ with respect to the first dielectric and inner segmented electrode. In Figure 1e, inner segmented electrode 165 has a substantially uniform cross-section (thickness) and variable capillary hole density (spacing) defined in the first dielectric 170 along the longitudinal length of the reaction chamber 155. While, in Figure 1f, the inner segmented electrode 165 has a non-uniform cross-section (thickness) and substantially uniform capillary density (spacing) defined in the first dielectric along the longitudinal length of the reaction chamber 155. The cross-sectional thickness of the inner segmented electrode 165, the density (spacing) of the capillaries 195 defined in the first dielectric 170, and/or the diameter of the capillaries 195 in the first dielectric 170 may be varied along the longitudinal length of the reaction chamber to achieve substantially uniform flow therein.

In operation, the fluid to be treated enters the inlet 160 and passes into the hollow inner U-shaped segmented electrode 165. Once within the hollow portion of the inner segmented electrode 165, the fluid to be treated is received in the holes 146 defined in the electrode segments that comprise the inner electrode and passed out through the capillaries 195 defined in the first dielectric 170.

Multiple annular reactors may be combined in a single system. By way of example, Figure 2a is a longitudinal cross-sectional view of a system having two annular reactors, while Figure 2b shows a lateral cross-sectional view of a system having eight reactors 210 enclosed in a common housing 205. The space in the housing 205 between the reactors 210 is filled with a dielectric material 215 to ensure that all of the fluid to be treated passes through the plasma region 155 of a reactor 210. The system may be designed to include any number of reactors to be arranged as desired within the housing. This embodiment is particularly suited for the treatment of relatively large flow rates of fluid to be treated wherein a relatively large reactor system is desirable. By way of example, each reaction chamber shown in Figures 2a and 2b may be configured similar to that shown and described with respect to Figure 1a-1f.

Instead of the reactor having an annular or tubular shape as shown and described in the embodiments thus far, the reactor may have a rectangular shape as shown in Figures 3a and 3b. The dimensions, e.g., the length, width and gap

length, of the reactor 300 may be modified, as desired, to accommodate specific applications. Reactor 300 has an inlet 350 connected to the reaction chamber by a transition conduit 310, as in the foregoing embodiments. The reaction chamber itself includes a second conductive electrode 340, preferably extending substantially the full width and length of the reaction chamber. Conductive electrode 340 is embedded in a second dielectric plate 315. A first dielectric plate 330 having holes or perforations therein that form capillaries is in direct contact with an inner segmented electrode 325 comprising a plurality of electrode segments. By way of example, each electrode segment is a hollow shaped ring or washer, as shown in Figures 1c and 1d. A hollow tube 335 is connected to the segmented electrode 325 that may be used as a conduit through which a supply of gases may be fed to improve the stability or optimize chemical reactions in the plasma. Chemical reactions take place in a plasma region that includes the capillaries defined in the first dielectric 330 as well as the area between the two dielectrics 315, 320. The treated fluid is discharged from the transition conduit 310' and through the outlet 305. The outside housing 360 of the reactor 300 is preferably made of a dielectric material.

Multiple rectangular plate reactors such as the one shown in Figures 3a and 3b may be combined in a single reactor. Figure 4, for example, shows a system 400 having four rectangular plate reactors 410 placed substantially parallel with respect to each other and encased in a common housing 415. The space within the housing 415 between the reactors 410 is filled with a dielectric material to ensure that all of the fluid to be treated is channeled through the plasma region of one of the reactors. This embodiment is particularly well suited for applications in which a relatively large flow rate of contaminated gas is to be treated and a relatively large combined reactor system is desirable.

In the embodiments shown in Figures 1-4, the dimensions of the reaction chamber may be selected as desired such that the residence time of the contaminants within the plasma regions is sufficient to ensure destruction of the contaminant to the desired level, for example, destruction down to the contaminants down to the molecular level.

Below are four exemplary reaction mechanisms that play an important role in plasma enhanced chemistry. Common to all mechanisms are electron impact dissociation and ionization to form reactive radicals. The four reaction mechanisms are summarized in the examples below:

(1) <u>oxidation</u>: e.g. conversion of CH_4 to CO_2 and H_2O

$e^- + O_2$ ® $e^- + O(^3P) + O(^1D)$

$O(^3P) + \mathbf{CH_4}$ ® $CH_3 + OH$

$CH_3 + OH$ ® $CH_2 + H_2O$

$CH_2 + O_2$ ® $H_2O + CO$

$CO + O$ ® CO_2

(2) <u>reduction</u>: e.g. reduction of NO into $N_2 + O$

$e^- + N_2$ ® $e^- + N + N$

$N + \mathbf{NO}$ ® $N_2 + O$

(3) <u>electron induced decomposition</u>: e.g. dissociative electron attachment to CCl_4

$e^- + \mathbf{CCl_4}$ ® $CCl_3 + Cl^-$

$CCl_3 + OH$ ® $CO + Cl_2 + HCl$

(4) <u>ion induced decomposition</u>: e.g. decomposition of methanol

$e^- + N_2$ ® $2e^- + N_2^+$

$N_2^+ + \mathbf{CH_3OH}$ ® $CH_3^+ + OH + N_2$

$CH_3^+ + OH$ ® $CH_2^+ + H_2O$

$CH_2^+ + O_2$ ® $H_2O + CO^+$

By way of example, in the foregoing embodiments the electrode segments comprising the segmented electrode have been shown and described as a hollow shaped ring or washer. However, the electrode segments may be configured in many different ways. Figures 5-8 show the configuration of a single electrode segment and an associated capillary in the first dielectric. Although only a single capillary and associated electrode segment is shown, the same electrode segment structure and arrangement may be used for a plasma reactor having multiple capillaries. Figure 5a is a cross-sectional view of a first embodiment of a hollow pin or cylinder shaped electrode segment 520 inserted partially into a respective capillary 510 defined in a first dielectric 505. In an alternative embodiment, the electrode

segment 520 may be disposed above, substantially flush with the dielectric, or extend any desired depth into the capillary 510. Since the electrode segment is hollow the fluid to be treated may be passed through the electrode segment and into the capillaries of the first dielectric and/or through a channel defined between the two dielectrics. Accordingly, treatment of the fluid by exposure to the plasma may occur in the capillaries and/or the channel.

Figures 6a and 6b show a cross-sectional view and a top view, respectively, of a solid segmented electrode 610 in the shape of a pin inserted partially into a capillary 600 defined in a first dielectric 605. In an alternative embodiment, the electrode segment 610 may be disposed above, substantially flush with, or inserted to any desired depth into the capillary 600. The electrode segment 610 may be solid or porous. If a porous electrode 610 is used, the fluid to be treated may be passed directly through the electrode segment thereby optimizing its exposure to the plasma discharge that occurs within the capillary. Since the fluid to be treated when passed through the electrode segment may be treated by the plasma discharge created in the capillary 600 itself, in this case, the second electrode and second dielectric may be eliminated altogether. Another advantage to using a porous electrode 610 is that it also serves as a conduit for the supply of gas to improve the stability, optimize the chemical reactions with the plasma, or perform chemical reactions within the plasma.

In Figures 6a and 6b the electrode segment has a blunt end, e.g., substantially flat , round, concave, or convex, whereas in an alternative embodiment shown in Figure 7a and 7b the electrode segment 700 terminates in a pointed tip. The exemplary electrode segment shown in both embodiments has a cylindrical shape, however, any desired shape may be used. Similarly, the shape and/or dimensions of the capillary 600, 710 need not correspond to that of the electrode segment 610, 700, respectively, but instead can be any shape, length, or angle of direction through the dielectric. Figures 6b and 7b are top views of the electrode segment and dielectric of Figures 6a, 7a, respectively. It is clear from the top views in Figures 6b, 7b that the diameter of the electrode segment 610, 700 is substantially equal to the diameter of the capillary 600, 710. The electrode segment and its respective capillary, however, need not be substantially equal in diameter. In addition, the thickness of the first dielectric need not be substantially uniform and can vary over the length of the reactor. The capillaries are used to sustain capillary plasma discharge and may also be used to introduce into the plasma region gases

to stabilize the discharge, or deliver reactants to the origin of the plasma for the purpose of performing chemistry.

Figures 8a-8e show yet another embodiment of the configuration of the segmented electrode wherein each electrode is substantially flat, e.g., a washer, ring or disk. In particular, Figures 8a and 8b show a cross-sectional view and a top view, respectively, of a solid substantially flat electrode segment 800 in the shape of a disk that is disposed over the capillary 810 so as to be substantially flush and in contact with the first dielectric 805. Alternatively, as shown in Figures 8c and 8d, the solid substantially flat electrode segment may extend partially into the capillary 810. It is also within the intended scope of the invention to use a substantially flat electrode segment 820 having a hole 811 defined therein to form a ring or washer, as shown in Figures 8e and 8f.

Different configurations for the electrode segment and its associated capillary may be used based on the following conditions: i) whether the electrode segment is solid, hollow, or porous; ii) the outer and/or inner shape of the electrode segment; iii) the dimensions of the electrode segment; and iv) whether the electrode segment is disposed above, substantially flush with the dielectric, or inserted at a predetermined depth into the capillary.

The portion of the reaction chamber shown in Figure 1d includes a second dielectric 115, whereas the second dielectric has been omitted in the embodiments shown in Figures 5a, 5b, 6a, 6b, 7a, 7b, 8a-8f. Any of these configurations in which the segmented electrode is hollow or made of a porous material may be implemented with or without a second dielectric and second electrode.

It is also within the intended scope of the invention to define auxiliary channels of any shape, dimension, or angle of direction in the first dielectric that do not have an associated electrode segment. Figure 9a and 9b show a cross-sectional view and a top view, respectively, of an exemplary solid annular (pin) electrode having a pointed tip that is partially inserted into a capillary 910. Auxiliary channels 915 are defined in the dielectric 905 substantially parallel to the capillary 910 into which the electrode segment 900 has been inserted. Fluids may be introduced into the auxiliary channels 915 to stabilize the plasma discharge or deliver reactants to the plasma for improving the chemical reactions. The auxiliary channels 915 may be defined in the dielectric at any desired angle. Figures 10a and 10b show two auxiliary channels 1015 defined in the dielectric 1005 so as to be in fluid

communication with the capillary 1010.

Each of the aforementioned segmented electrode configurations have been shown and described by way of example. The features of each embodiment may be modified or combined with those of other embodiments as desired. The invention is not to be limited to the particular shape, dimension, number, or orientation of the electrodes or capillaries shown by way of example in the figures.

The aforementioned embodiments have been described with reference to the treatment or purification of a contaminated fluid. Another application for the use of the plasma reactor in accordance with the present invention is for treating or cleaning a solid or porous surface. Figure 11 is a schematic diagram of an exemplary surface cleaning system in accordance with the present invention. System 1100 includes a reactor 1125 including a perforated dielectric plate and a segmented electrode together represented as 1105. The segmented electrode and dielectric plate may be configured in accordance with any of the embodiments described above. Plasma is generated in the capillaries and discharged therefrom in the form of plasma jets 1110. An object is positioned so that the surface of the object to be cleaned is exposed to the plasma jets 1110. In the embodiment shown in Figure 11, the object 1115 to be cleaned is positioned between two dielectrics 1105, 1120. Alternatively, the second dielectric 1120 may be eliminated, as described above.

In yet another application, the segmented electrode capillary discharge plasma system may be used to purify gases. Figure 12a is a schematic diagram of an exemplary air handler with a segmented electrode capillary discharge plasma device for cleaning contaminated gases. The air to be purified is received in the inlet 1200, mixes with air from a return inlet 1210, and then passes through a segmented electrode capillary discharge plasma air cleaning device 1220 before exiting the system. Figure 12b is an enlarged view of an exemplary segmented electrode capillary discharge plasma air cleaning device 1220 that includes a plurality of segmented electrodes and opposing perforated dielectric plates arranged substantially parallel to one another. Plasma regions are formed between the segmented electrode and opposing dielectric plates. In the exemplary embodiment shown in Figure 12a the segmented electrode capillary discharge plasma air cleaning device 1220 is arranged after the supply air and mixing air are combined. The reactor system could alternatively be designed so that the segmented electrode capillary discharge plasma air cleaning device 1220 is arranged at any one location

or at multiple locations within the system.

The segmented electrode capillary discharge, non-thermal plasma reactors in accordance with the present invention can be used to perform a variety of chemical reactions by exposing a fluid or surface containing the desired reactants to the high density plasma region where various processes such as oxidation, reduction, ion induced decomposition, or electron induced decomposition efficiently allow for chemical reactions to take place. The fluid to be treated may be fed either through the channel between the two dielectrics (transversely to the flow of the plasma discharged from the capillaries of the dielectric) and/or through the capillaries themselves (the point of origin of the plasma). Examples of reactions include: chemistry on various organic compounds such as Volatile Organic Compounds (VOCs) either single compounds or mixtures thereof; semi-volatile organic compounds, Oxides of Nitrogen (NOx), Oxides of Sulfur (SOx), high toxic organics, and any other organic compound that can be in the form of vapors of aerosols. In addition, the reactor can be used to pretreat combustion air to inhibit formation of Nox and increase fuel efficiency. Additional uses of the plasma includes the generation of ozone and ultraviolet light, and treatment of contaminated surfaces.

Thus, while there have been shown, described, and pointed out fundamental novel features of the invention as applied to a preferred embodiment thereof, it will be understood that various omissions, substitutions, and changes in the form and details of the devices illustrated, and in their operation, may be made by those skilled in the art without departing from the spirit and scope of the invention. For example, it is expressly intended that all combinations of those elements and/or steps which perform substantially the same function, in substantially the same way, to achieve the same results are within the scope of the invention. Substitutions of elements from one described embodiment to another are also fully intended and contemplated. It is also to be understood that the drawings are not necessarily drawn to scale, but that they are merely conceptual in nature. It is the intention, therefore, to be limited only as indicated by the scope of the claims appended hereto.

Claims

What is claimed is:

1. A plasma reactor comprising:

a first dielectric having at least one capillary defined therethrough; and

a segmented electrode including a plurality of electrode segments, each electrode segment disposed proximate an associated capillary.

2. The plasma reactor in accordance with claim 1, wherein at least one of said electrode segments is shaped as a pin.

3. The plasma reactor in accordance with claim 2, wherein said pin has a blunt tip oriented proximate the capillary.

4. The plasma reactor in accordance with claim 2, wherein said pin has a pointed tip oriented proximate the capillary.

5. The plasma reactor in accordance with claim 1, wherein at least one of said electrode segments is shaped as a substantially flat ring having a hole defined therethrough.

6. The plasma reactor in accordance with claim 1, wherein at least one of said electrode segments is shaped as a substantially flat disk.

7. The plasma reactor in accordance with claim 6, wherein said at least one electrode segment is solid.

8. The plasma reactor in accordance with claim 6, wherein said at least one electrode segment is porous.

9. The plasma reactor in accordance with claim 1, wherein at least one electrode segment is porous.

10. The plasma reactor in accordance with claim 1, wherein at least one electrode segment is hollow.

11. The plasma reactor in accordance with claim 1, wherein at least one of said electrode segments is disposed proximate and separated a predetermined distance from said first dielectric.

12. The plasma reactor in accordance with claim 1, wherein at least one of said electrode segments is disposed substantially flush and in contact with said first dielectric.

13. The plasma reactor in accordance with claim 1, wherein at least one of said electrode segments is partially inserted in the capillary.

14. The plasma reactor in accordance with claim 1, wherein at least one of said electrode segments is fully inserted into the capillary.

15. The plasma reactor in accordance with claim 1, further comprising:

a second electrode; and

a second dielectric proximate said second electrode, said first and second dielectrics being separated by a predetermined distance to form a channel therebetween.

16. The plasma reactor in accordance with claim 15, wherein said second electrode is a substantially planar plate.

17. The plasma reactor in accordance with claim 15, wherein said second electrode is a segmented electrode including a plurality of electrode segments.

18. The plasma reactor in accordance with claim 1, wherein the first dielectric has a plurality of capillaries defined therethrough, the capillaries being arranged so that spacing between adjacent capillaries is substantially equal.

19. The plasma reactor in accordance with claim 1, wherein the first dielectric has a plurality of capillaries defined therethrough, the capillaries being arranged so that spacing between adjacent capillaries is not equal.

20. The plasma reactor in accordance with claim 1, wherein said segmented electrode has a substantially uniform thickness.

21. The plasma reactor in accordance with claim 1, wherein said segmented electrode has a non-uniform thickness.

22. The plasma reactor in accordance with claim 1, wherein said first dielectric has an auxiliary channel defined therethrough.

23. The plasma reactor in accordance with claim 1, wherein said first dielectric has an auxiliary channel defined therein and in fluid communication with the capillary.

24. Method of treating a fluid in a plasma reactor including a first dielectric having at least one capillary defined therethrough, and a segmented electrode including a plurality of electrode segments, each electrode segment disposed proximate an associated capillary, said method comprising the steps of:

passing the fluid to be treated through at least one electrode segment and capillary; and

exposing in the capillary the fluid to be treated to the plasma discharge prior to exiting from the capillary.

25. The method in accordance with claim 24, wherein the electrode segment is hollow.

26. The method in accordance with claim 24, wherein the electrode segment is made of a porous material.

27. The method in accordance with claim 24, further comprising the steps of:

passing the fluid to be treated through a channel defined between the first dielectric and a second dielectric; and

exposing in the channel the fluid to be treated to a plasma discharged from the capillary.

28. Method of treating a fluid in a plasma reactor including a first dielectric having at least one capillary defined therethrough, and a segmented electrode including a plurality of electrode segments, each electrode segment disposed proximate an associated capillary, said method comprising the steps of:

passing the fluid to be treated through a channel defined between the first dielectric and a second dielectric; and

exposing in the channel the fluid to be treated to a plasma discharged from the capillary.

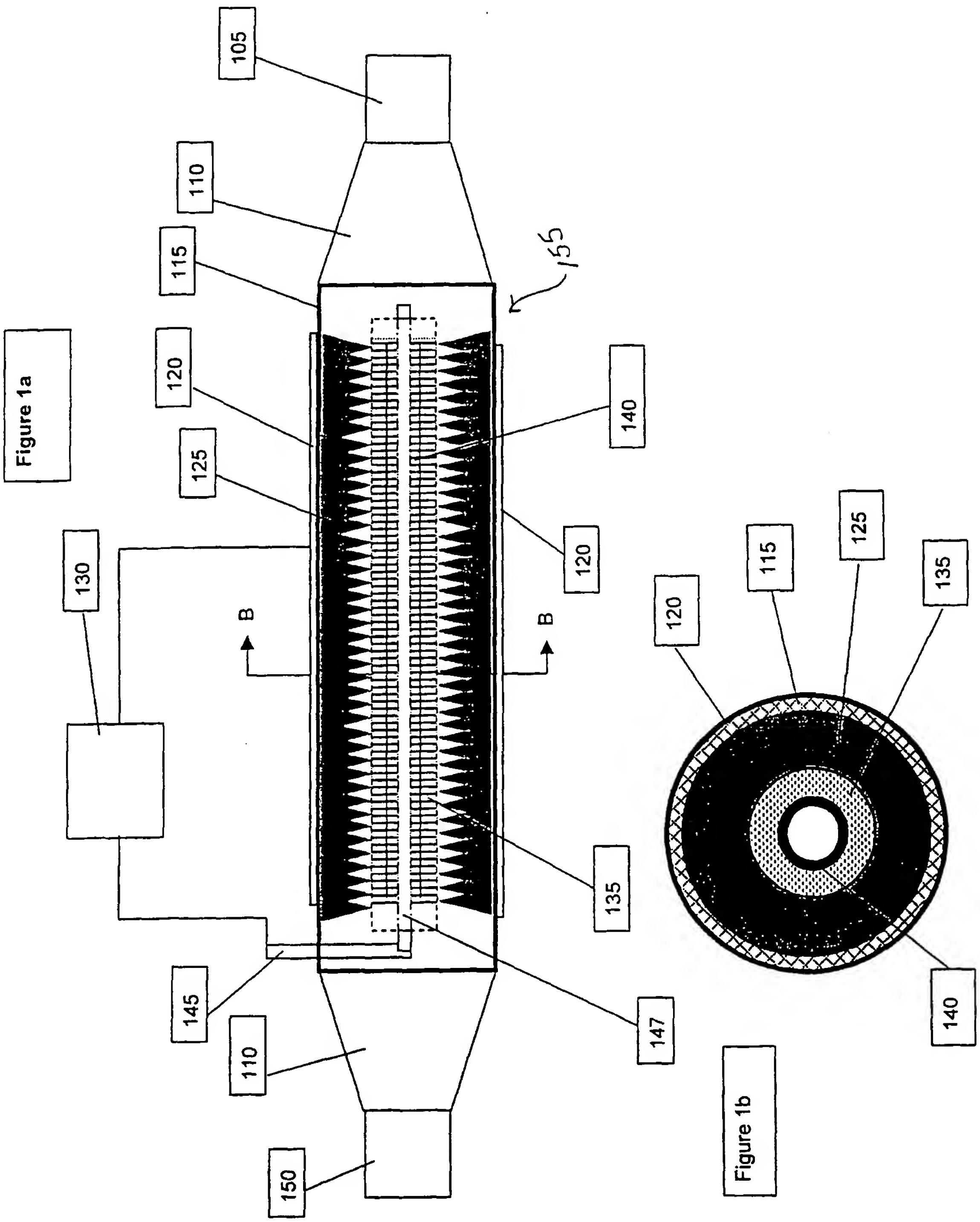


Figure 1a

Figure 1b

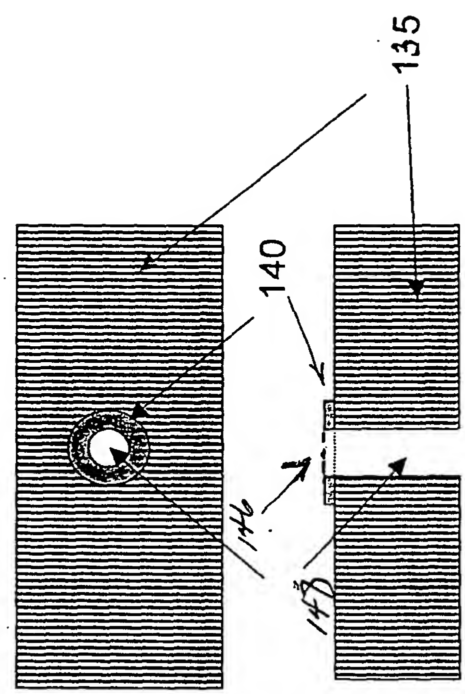


Figure 1c

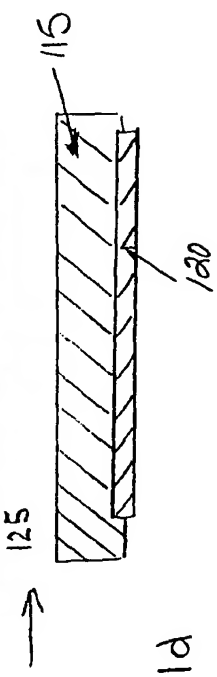


FIG.1d

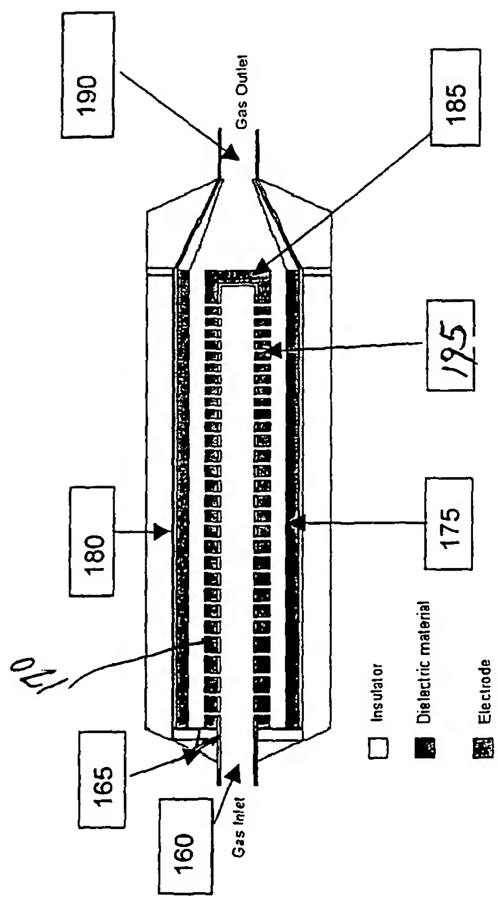


Figure 1e

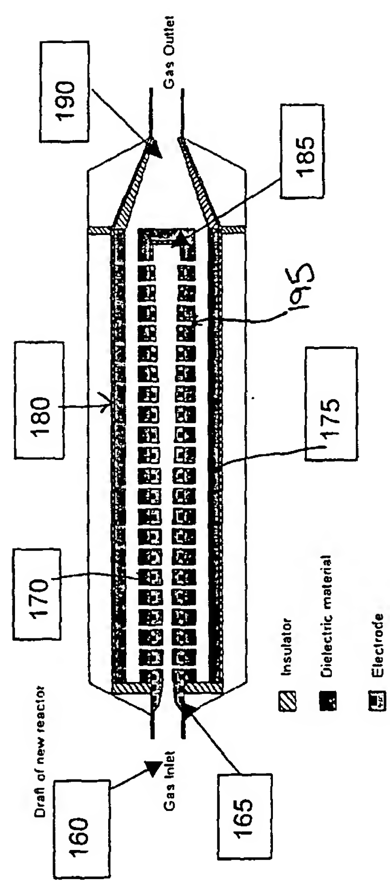


Figure 1f

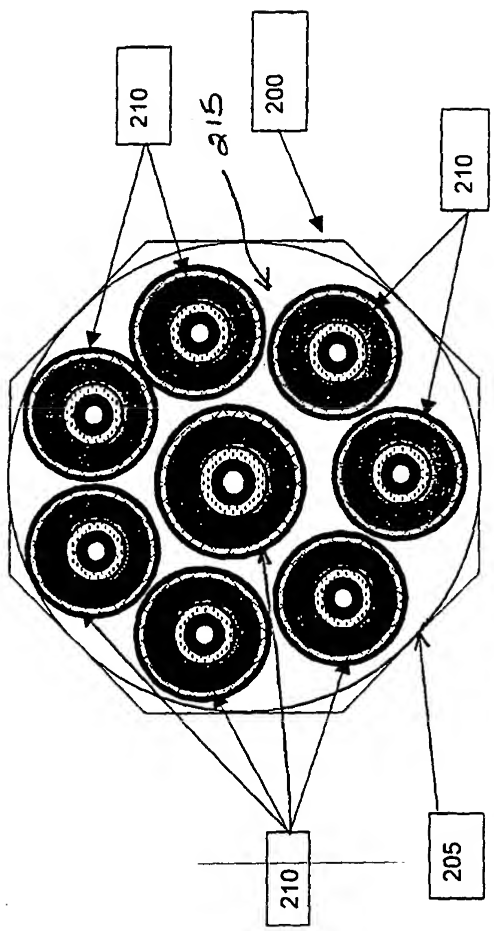


Figure 2b

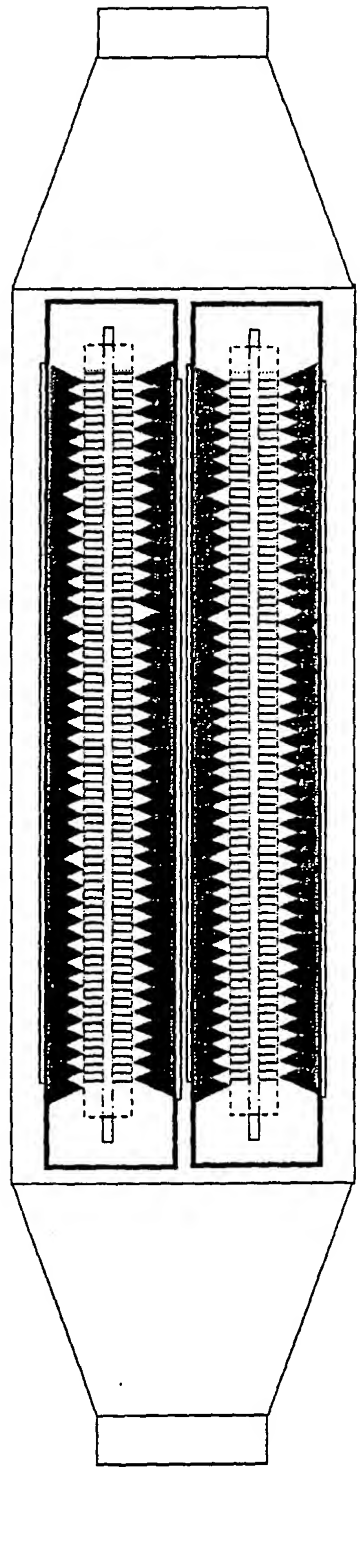


Figure 2a

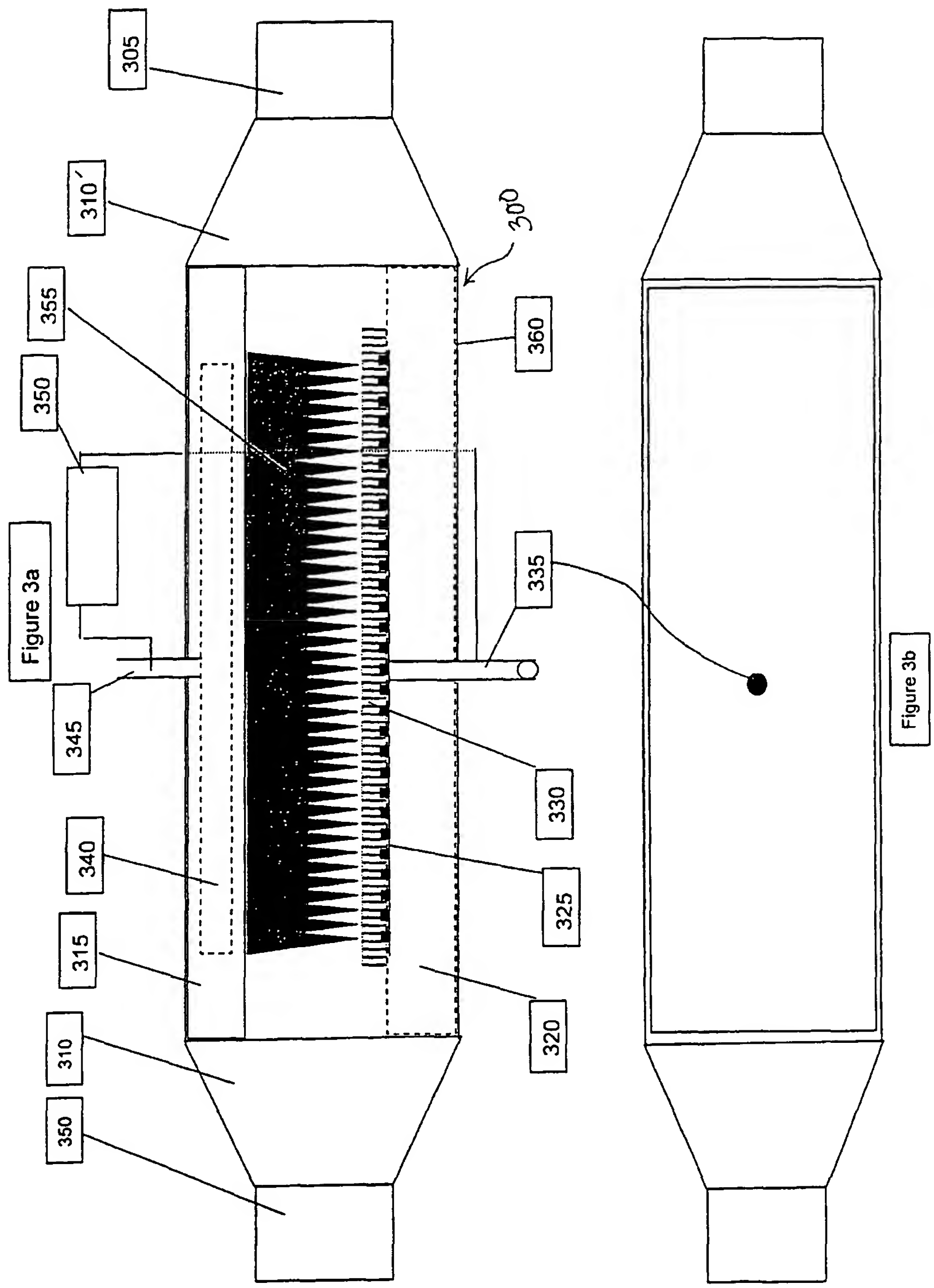


Figure 3a

Figure 3b

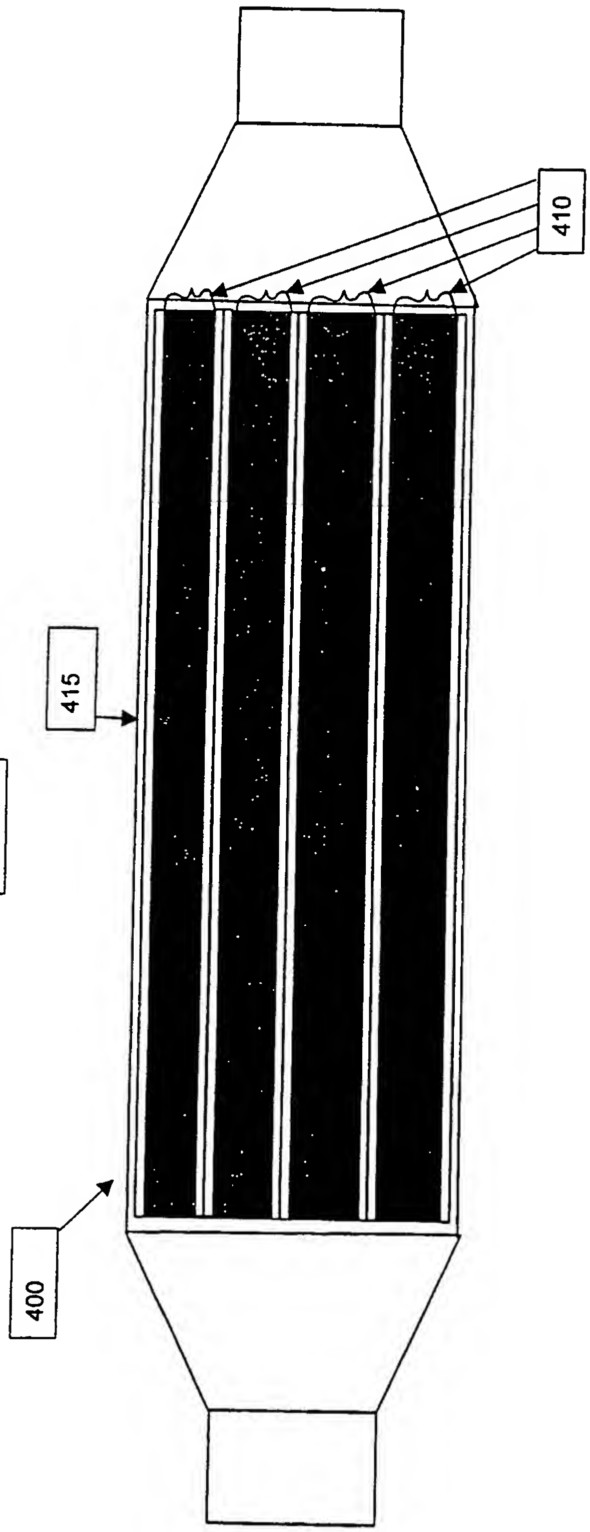


Figure 4

Figure 5a

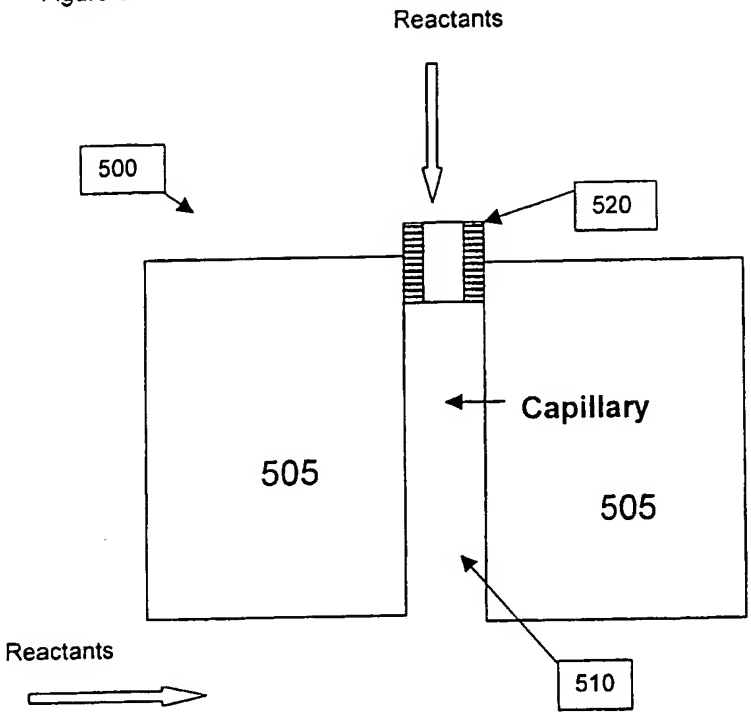
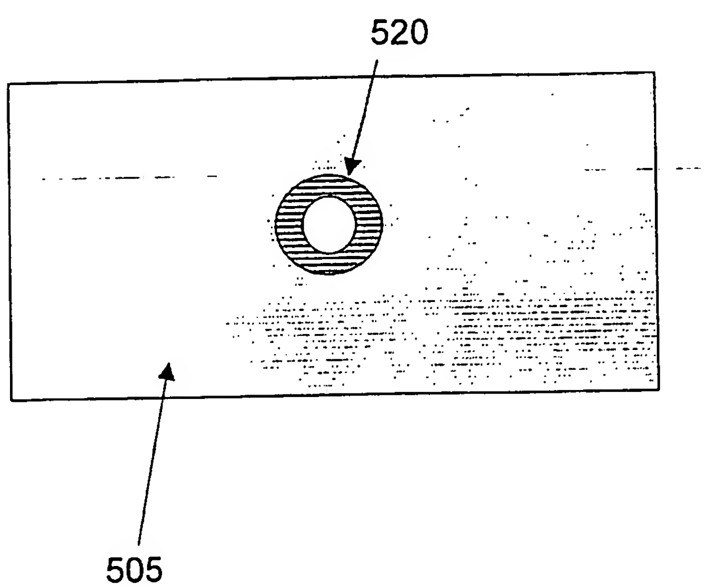


Figure 5b – Top View



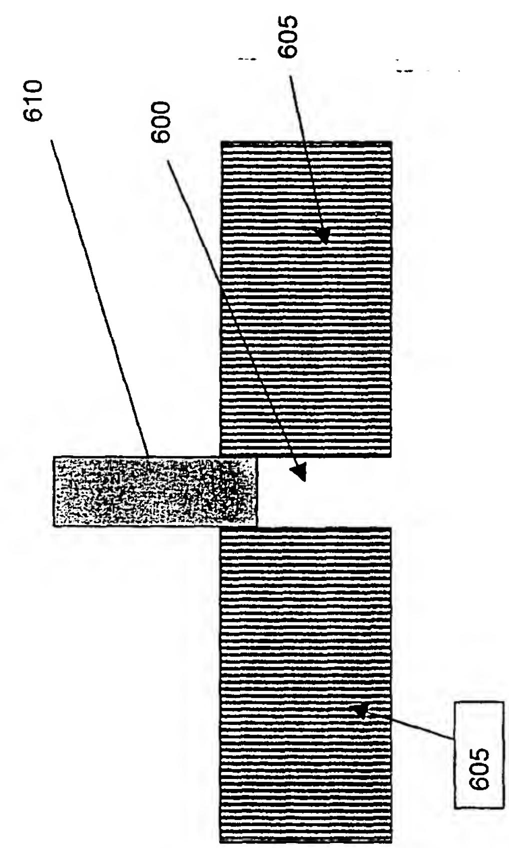


Figure 6a

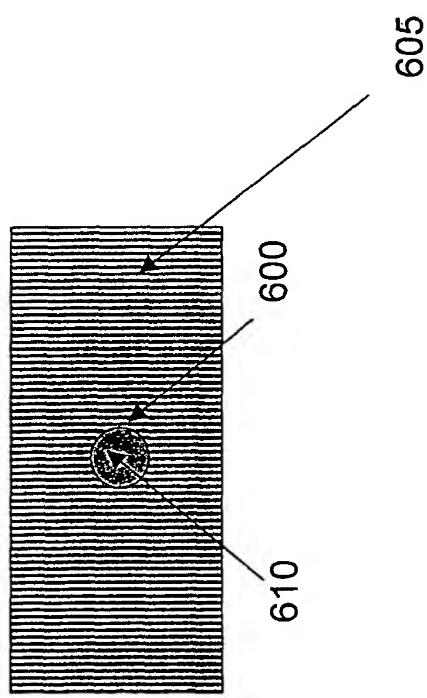


Figure 6b

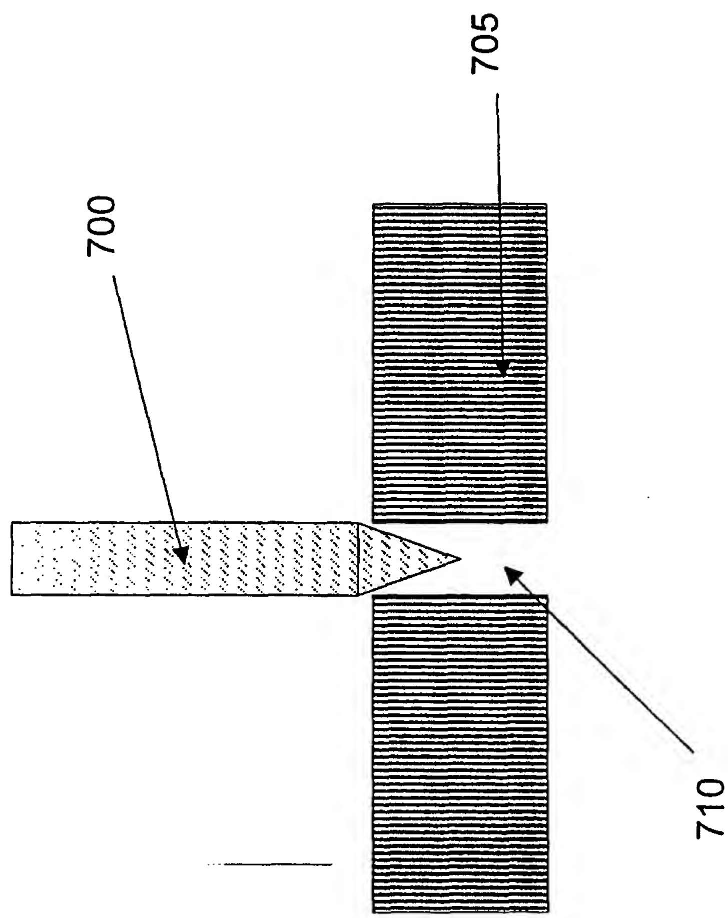


Figure 7a

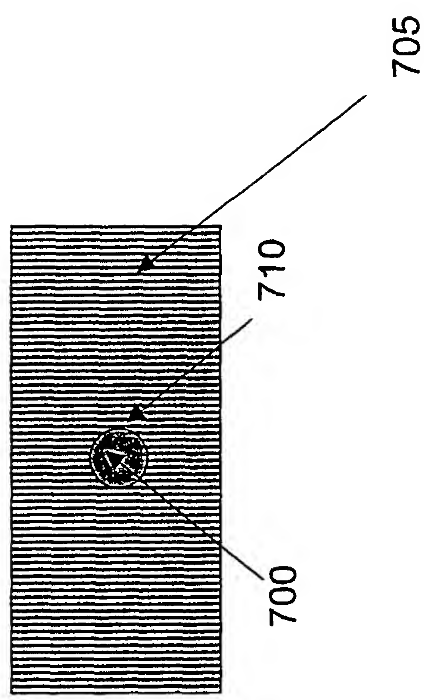


Figure 7b

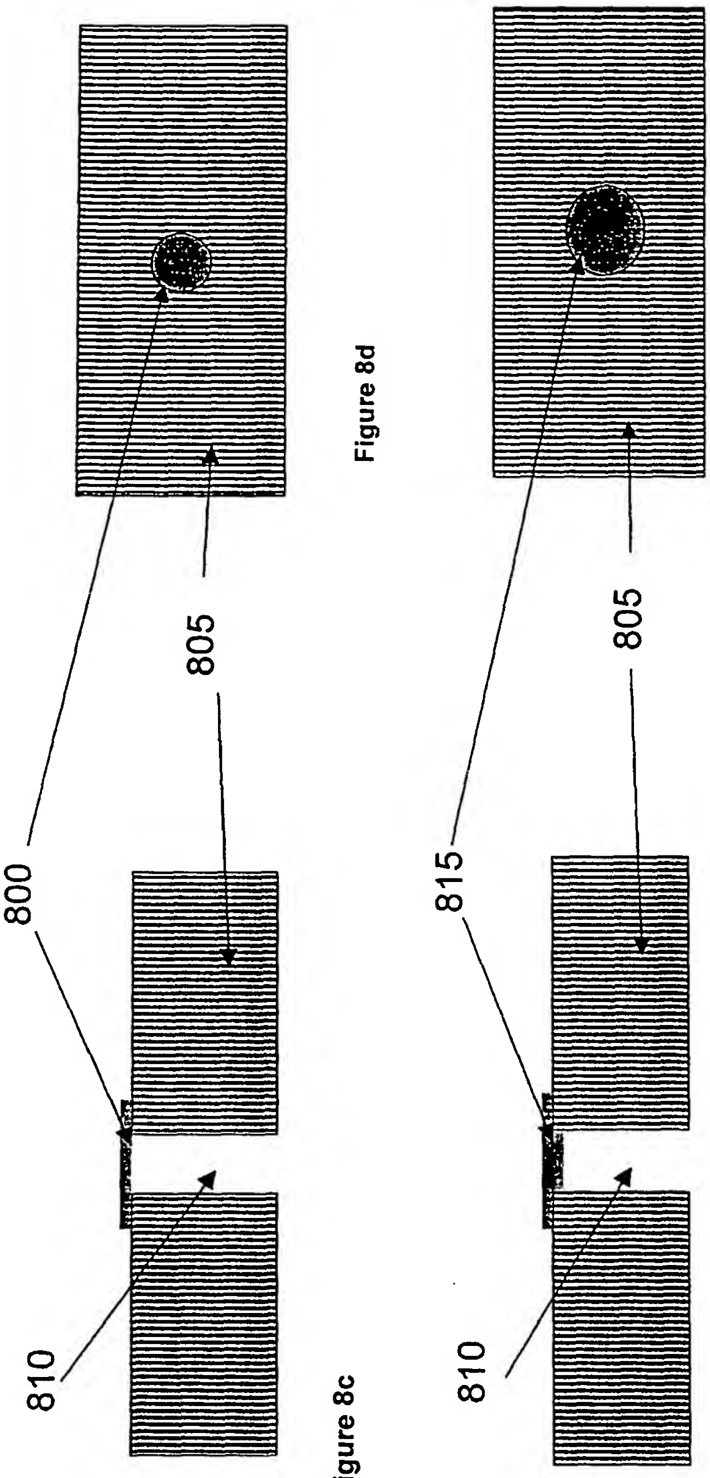


Figure 8a

Figure 8b

Figure 8c

Figure 8d

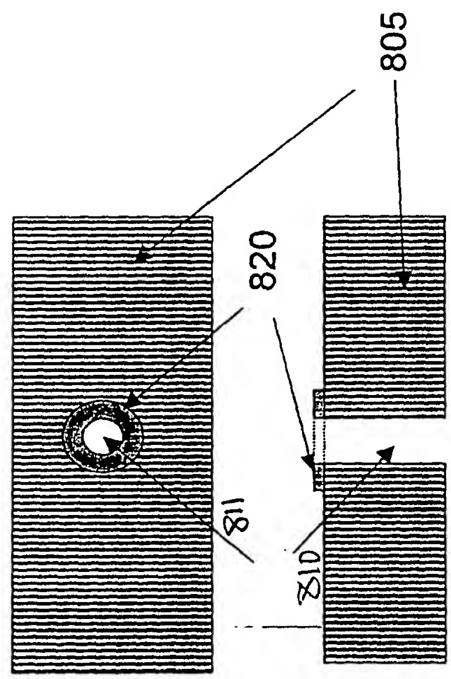


Figure 8f

Figure 8e

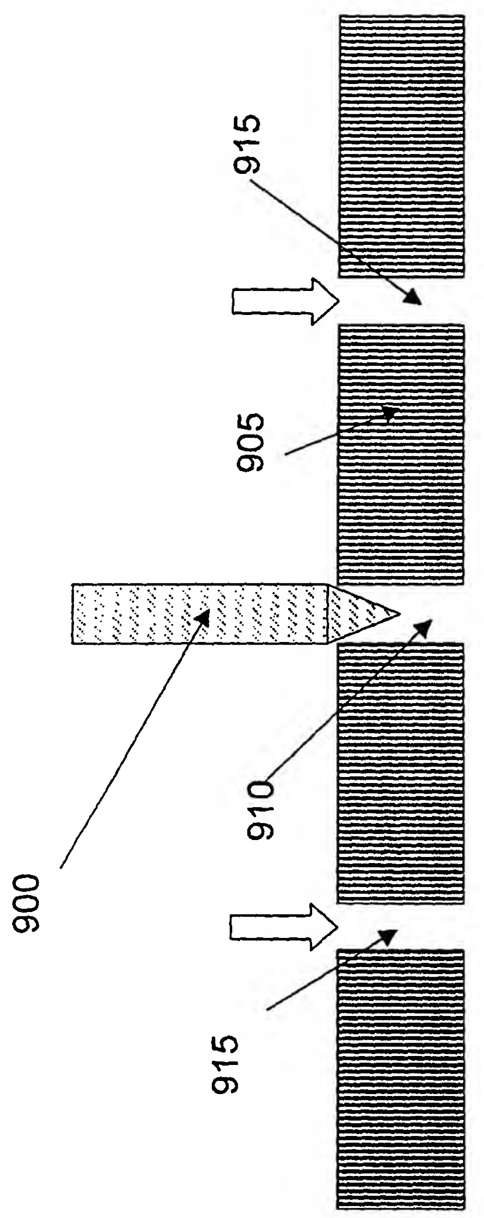


Figure 9

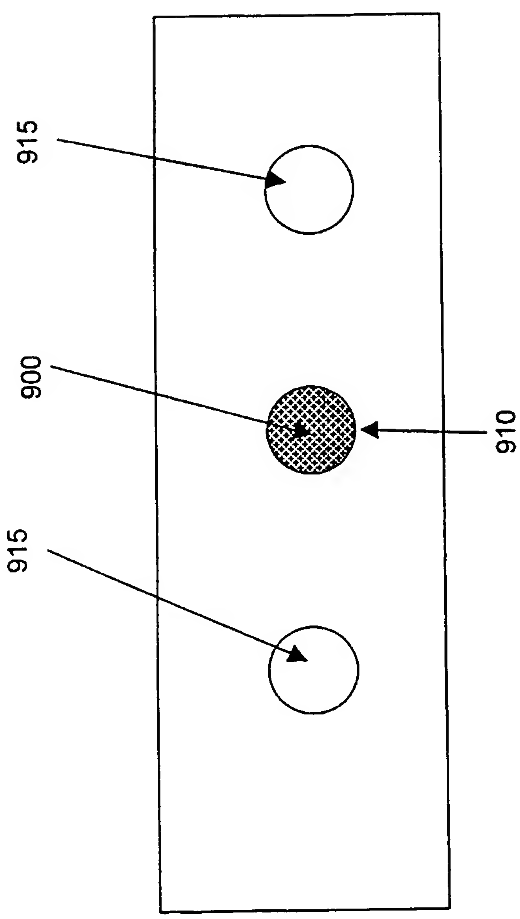


Figure 9b

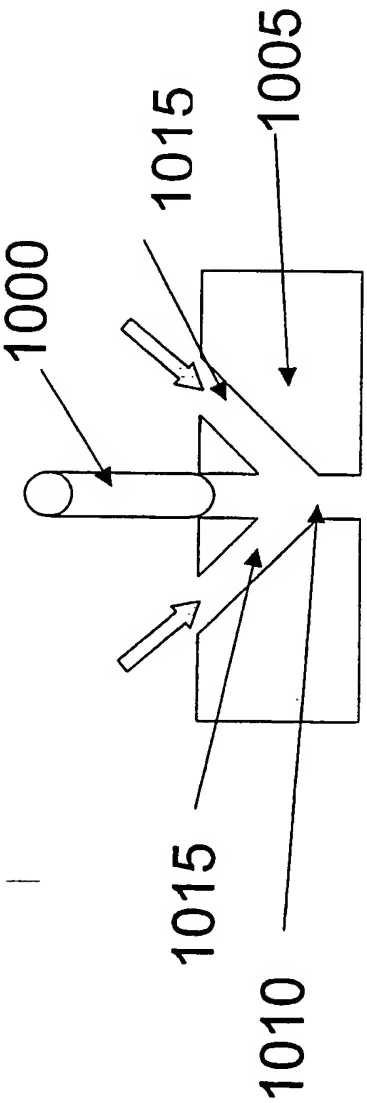


Figure 10a

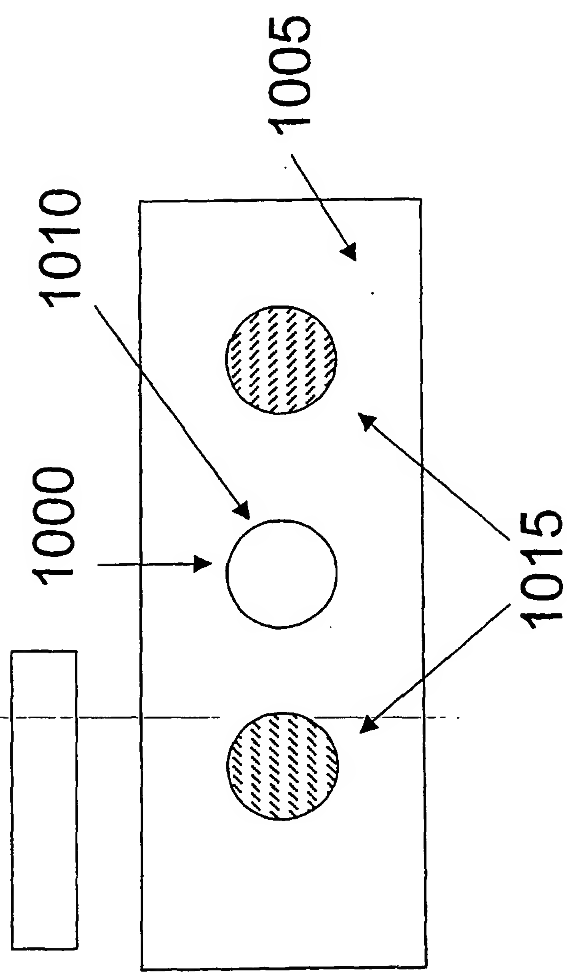


Figure 10b

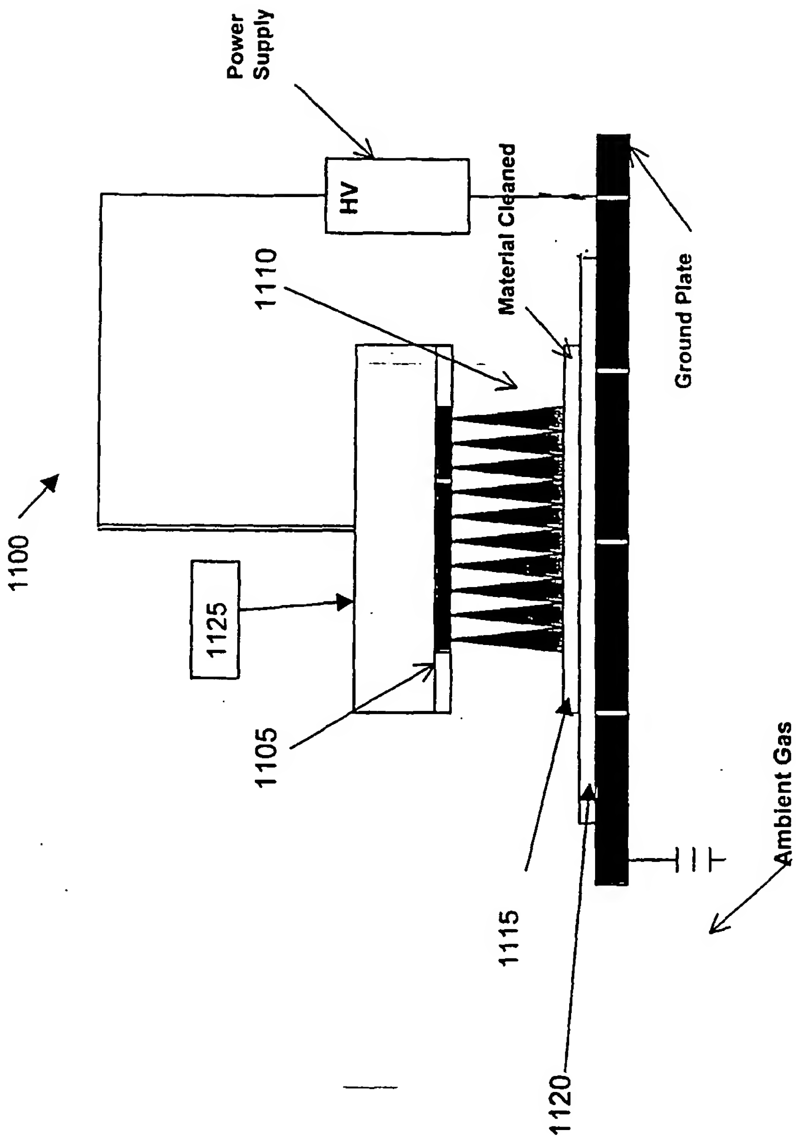

Power Supply
HV
Material Cleaned
1110
Ground Plate
1100
1125
1105
Ambient Gas
1115
1120

Figure 11

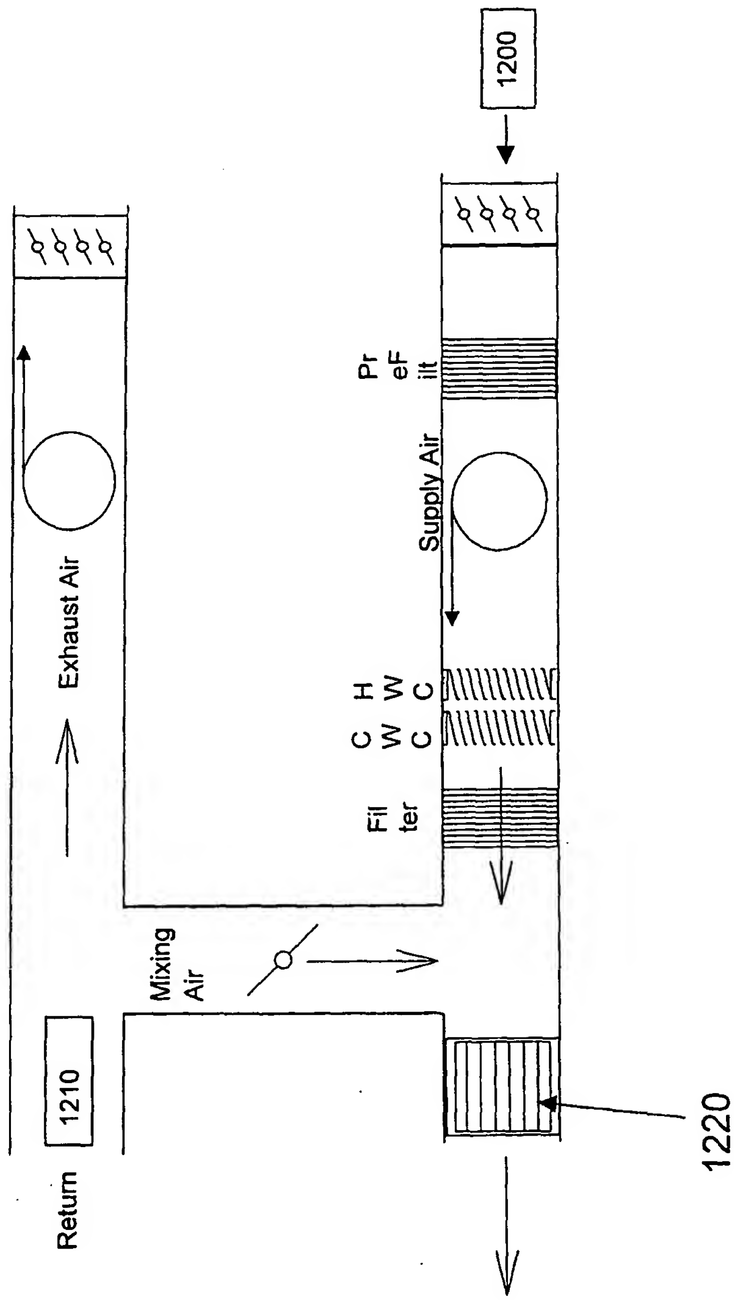

1200
Pr
eF
ilt
Supply Air
Exhaust Air
H
W
C
C
W
C
Fil
ter
Mixing
Air
1210
Return
1220

Figure 12a

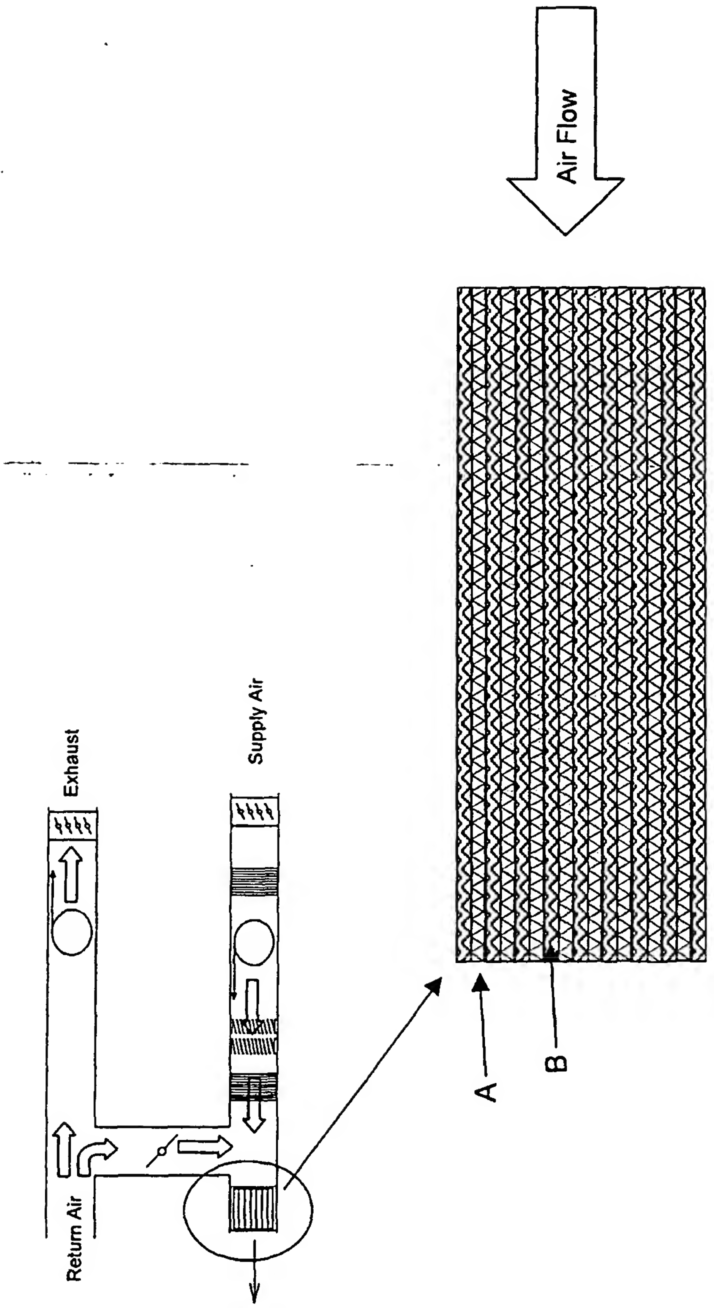


Figure 12B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/34113

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : G01N 21/73; F41B 6/00
US CL : 315/111.21, 111.81, 313/231.410; 356/316
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 315/111.21, 111.81, 313/231.410; 356/316

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

WEST, EAST, DIALOG

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,033,355 A (Goldstein et al) 23 July 1991 (23.07.91). See entire document.	1-7, 24-27 and 28
X	US 5,062,708 A (Liang et al) 05 November 1991 (05.11.91). See entire document.	8-23
X	US 5,476,501 A (Stewart et al) 19 December 1995 (19.12.95). See entire document.	1-28
Y	US 4,885,074 (Suske et al) 05 December 1989. (05.12.89) See entire document.	1-28

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
12 FEBRUARY 2001	26 MAR 2001

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	JIMMY VU
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Form PCT/ISA/210 (second sheet) (July 1998)*